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The Application of Set-Based Concurrent Engineering to Enhance the Design Performance of Surface Jet Pump

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Abstract: - Set-Based Concurrent Engineering (SBCE) is an approach that has the capability to improve the efficiencies of the product development process. SBCE provides an environment where design space is explored thoroughly which lead to enhance innovation. This is achieved by considering an alternative set of solutions after gaining the right knowledge to support decision to narrow down the set of solutions until the single optimal design solution is reached. This paper presents a novel application SBCE in order to generate alternative design to enhance the efficiency of the Surface Jet Pump (SJP) in term of its productivity and performance of producing the oil and gas in oil and gas well.

Key-words: - lean product development, set-based concurrent engineering, product development, set-based design, trade-off curve, surface jet pump.

1 Introduction

The demand for efficient and cost effective products has put an immense pressure on manufacturing companies to deliver products that will satisfy their customers. In fact, 70-80% of the product cost is determined in the conceptual development of the product lifecycle [1]. The Set-Based Concurrent Engineering (SBCE) approach has shown a huge potential in improving the process of product development and became great alternative to traditional point-based approach. However, its constructive measure in real industrial applications is still ambiguous [2]. This is due to lack of clear guidelines on how to implement the SBCE in the industries besides a limited number of real case studies [3]. Thus, this paper is to clarify the gap in the application of the details and well-structured SBCE process model in the SJP case study and is structured into three sections, namely a review of the SBCE related literature, SBCE case study and finally, conclusion.

2 A review of the SBCE related literature

The literature emphasises on the importance of having SBCE in product development application [4] [5] [6] [7]. This is because SBCE represents the definition of the process that will be followed to develop a product. Toyota is famous for its production system, but it is commonly presumed that this is not the only factor of the success, because Toyota Product Development System (TPDS) is also playing an important role in this achievement [8]. [9] proved that the real success of

Japanese manufacturers' is not derived from their production system, but from the TPDS. Later on, [7] shown a detailed description of the 13 principles that shaped the Toyota Product Development system. They provided a conceptual model called Lean Product Development System, which is divided into three subsystems: Process, Skilled People, Tools and Technology which entails of 13 principles.

SBCE is considered as the core enabler in Lean Product Development as it represents the process that guides the development of a product in a lean environment [10]. SBCE works on entirely different principles than point-based advance. A point-based design approach is the traditional PD practice where it only considers only one best solution and later it is iteratively modified till it meets the acceptable result. The SBCE approach considers it desirable to develop various sets of solutions in parallel rather than working with one idea at a time. SBCE mean; design participant practice SBCE by reasoning, developing, and communicating about a set of solution in parallel. As the design progressed, they gradually narrow their respective set of solution based on the knowledge gained. As they narrow, they commit to staying within the sets so that the others can rely on their communication [8].

[11] created the SBCE baseline model, consist of five phases which is 1) Define value, 2) Map design space, 3) Develop concept sets, 4) Converge on system, and 5) Detailed design as illustrated in Fig. 1. In addition, [11] and [3] described the SBCE in a step-by-step process in the SBCE process model. This is to ensure the implementation is followed correctly at the first time as illustrated in Fig. 2.

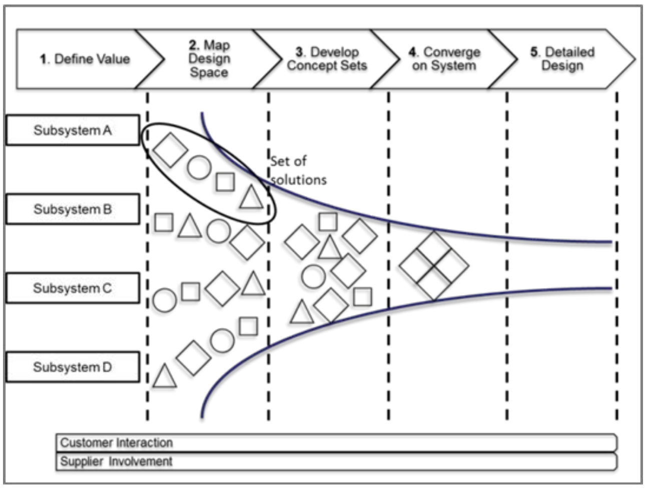

Fig. 1: The SBCE baseline model [11]

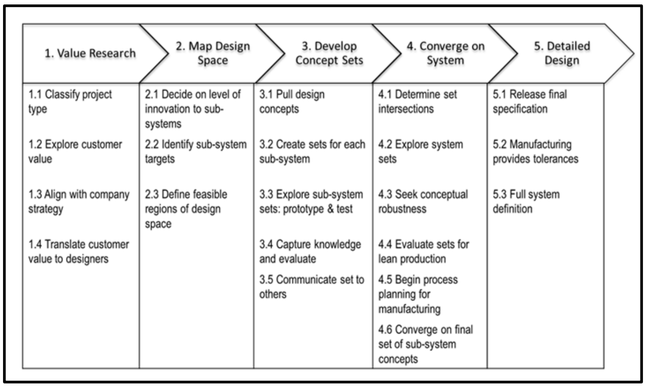

Fig. 2: The SBCE process model [3] [11]

There are limited numbers of SBCE case studies has been done to identify its potential and benefits to the industries [3] [12] [13]. However, there are no details of step-by-step application of the SBCE process model and its validation from the case studies**.** Therefore, the case study will clarify the gap in the application of the SBCE using a clear guideline of the SBCE process model.

3 The Surface Jet Pump Case Study

The SBCE process model was implemented during the case study of SJP in collaboration with Caltec Lmited. The SJP as shown in Fig. 3, is a device used to enhance productivity of oil or gas extraction in oil and gas well by using the energy from a high pressure fluid/gas to boost the pressure of a low pressure fluid/gas to obtain an intermediate pressure level. The main feature of SJP is to enhance performance of gas extraction what could be understood as an increase of pressure at the output or High Pressure (HP) source, the reduction in pressure on Low Pressure (LP) source by maintaining output parameters. The following paragraphs presents the selected activities of SBCE from Fig. 2 that have been used in the case study.

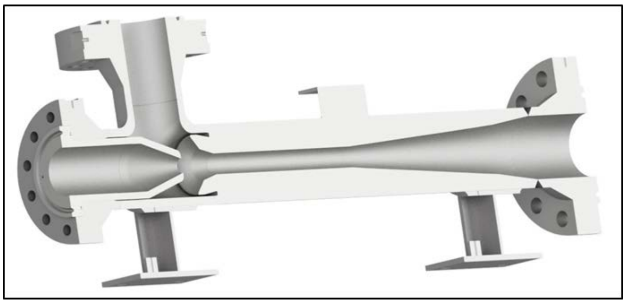

Fig. 3: Cross-section view of SJP courtesy from Caltec Ltd.

Phase 1: Define Value

The initial concept of the SJP is defined in Define Value stage, which has the subsequent SBCE activity.

1.2 Explore customer value

Customer needs must be understood to accurately define system targets specifically related to the increment of the design performance, which is the most important value in this case. Identified 38 values are listed in Fig. 4-B and then the values are classified into a singular value to confirm that customer needs are formed properly as shows in Fig. 4-B.

Through the Analytical Hierarchy Process (AHP) values that have been classified as high importance were analysed [14], where the result is illustrated in Fig. 4-D. Based on company prioritisation and the loads of importance rank from the AHP, the customer value attribute has been listed respectively as presented in Fig. 4-D. This led to define the key value attributes (KVA) as shown in Fig. 4-E where the 3 highest percentage were selected, these are; 1) Design Performance, 2) Manufacturability, 3) Cost and 4) Durability. Cost was classified as KVA due to company's preference choice which has the major impact in the creation of this order. The values which remain (reliability and installation) were assigned as values of consideration. The loads for the key value attributes in Fig. 4-E are calculated respectively with AHP value in Fig. 4-D. The values calculated are an approximate value. The equation are described as follows:

(1)

$$\text{Loads for} \text{KVA} = \frac{\text{AHP}_\text{P}}{\sum_{i=1}^{3} \text{AHP}_\text{P}} \text{ x } 100\%$$

Where;

AHP_P = AHP Priority percentage (e.g: Design performance; 22.3%)

$\sum_{i=1}^{3} \text{AHP}_\text{P}$ = Total sum of top 3 highest AHP priority percentage based on company prioritization order.

The calculation are as follows:

(2) Design performance: (23%/58%) x 100% = 38.5% (approx.)

(3) Manufacturability: (22%/58%) x 100% = 37.5% (approx.)

(4) Cost: (14%/58%) x 100% = 24.0% (approx.)

KVA	System Target
Design performance	1) HP Pressure ≥ 400 psig 2) LP Pressure ≤ 205 psig 3) Discharge Pressure ≥ 320psig 4) The nozzle is replaceable 5) No moving parts 6) Smooth surface inside the mixing tube 7) Easy to change and install 8) Great production rate performance
Manufacturability	1) Low complexity 2) Fastest possible way to manufacture
Cost	1) Low manufacturing cost 2) Maintenance free

Table 1: System target for KVA in the SJP case study

The next step, the system targets should be specified in order to explain how the value attributes will be reached. System targets should be analysed at the subsystem level to confirm their correct translation on subsystem targets. System targets as depicted in Table 1, are measurable values which represent key value attributes. Nevertheless, rarely several targets cannot be depicted by a numerical value.

A

Interviews and brainstorming

B

Define Value

No.	Value description
1	Cheaper possible manufacturing cost
2	No additional energy consumption
3	Maintenance free
4	Zero operational costs
5	Fastest possible manufacturing
6	Machining from very small to large scale
7	Shorter in length
8	Low complexity
9	Alignment of the tube (nozzle to the mixing tube)
10	Smooth surface inside the SJP (minimum friction)
11	Parametric relation between nozzle and diffuser
12	Adjustable nozzle
13	Meeting oil and gas standards from ASME B31.3, B16.5, ASME IX
14	Production rate performance (delivering results as per process design)
15	Possibility to connect to several wells
16	Reduced back pressure
17	No moving parts
18	Tolerant to pressures fluctuations
19	Lighter in weight
20	Noise level to be lower than 85dB
21	20 years lifecycle
22	Ability to handle Vibrations
23	Adjustable to different gases and fluids
24	Working conditions – temperature, pressure
25	Clog resistance
26	No leak
27	Not flammable
28	Easy to install
29	Can be installed in tight spaces
30	Minimum modification to existing pipework
31	Flexibility of sources orientation
32	Replaceable parts (nozzle, mixing tube) easy to change and install
33	Easy operation
34	Corrosion resistance
35	Erosion resistance
36	Stable in subsea environment
37	Strong type of material
38	Hard surface inside the SJP

C

Classification

No	Value Classification	No.
1	Cost	1, 2, 3, 4
2	Manufacturability	5, 6, 7, 8, 9, 10
3	Design Performance	11, 12, 13, 14, 15, 16, 17, 18, 19, 20
4	Reliability	21, 22, 23, 24, 25, 26, 27
5	installation	28, 29, 30, 31
6	Customisation	32, 33
7	Durability	34, 35, 36, 37, 38

Importance values

7 Values

D

Prioritisation

AHP Matrix Analysis

No	Value	AHP Priority (%)	Company Prioritisation
1	Cost	13.8%	3
2	Customisation	6.8%	6
3	Design Performance	22.3%	1
4	Manufacturability	21.6%	2
5	Reliability	15.7%	5
6	Durability	16.7%	4
7	Installation	3.1%	7

E

Key Value Attributes

Key Value Attributes	Load of importance
Design Performance	38.5%
Manufacturability	37.5%
Cost	24.0%

Values of consideration
Durability
Reliability
Customisation
Installation

Fig. 4: The different sub-activities and their results of the SBCE activity of 1.2 "explore customer value"

Phase 2: Map Design Space

In this phase the scope of the design work as well as feasible regions of the SJP design was defined.

2.1 Decide on the level of innovation to the subsystem

In the activity 2.1 “Decide on the level of innovation to the subsystem”, the SJP system structure was divided into subsystems as listed below and shown in Fig. 5 these are; Flanges (1), Nozzle (2), Body (3), Mixing Tube (4), and Mounts (5). The level of innovation is a colour-coded tool that is used to visualise the level of innovation needed for subsystems of a product as illustrated in Fig. 6-A.

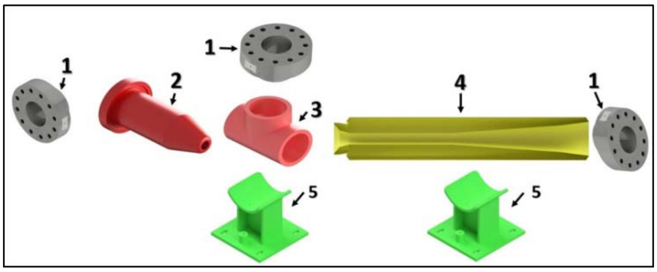

Fig. 5: Level of innovations of the SJP subsystem

High level of innovation is required for the nozzle (2) and body (3). The nozzle (2) determines the performance of the system. The function of the body (3) is to provide a suitable flow direction of the fluids as well as to integrate each of the components in the SJP. The mixing tube (4) has been classified as a medium innovation. Inside the mixing tube (4), HP and LP fluids from oil and gas well are mixed together to obtain the discharge pressure. In order to increase discharge pressure, mixing tube (4) needs a medium level of design changes to enhance system performance. Mounts (5) are defined as “Low innovation” to ensure proper absorption of the vibration. Flanges (1) are coded as “no change in the design”.

2.2 Identify subsystem target

In the activity 2.2 “Identify subsystem target”, feasible target for each subsystem is defined to prevent over engineering and supporting the development of innovation. From “Define value” phase, some of the system targets were adapted onto subsystem targets. The subsystem targets are listed correspondingly as presented in Fig. 6-B.

2.3 Define the feasible region of design space

In the activity 2.3 “Define the feasible region of design space”, design space is defined as the boundaries for designers and engineers to explore and communicate with many alternative conceptual design solutions.
Design space for the SJP and for the nozzle is presented in Fig. 6-C.

Phase 3: Develop Concept Sets

In phase 3, the sets of possible conceptual design solutions were developed for each SJP subsystem.

3.2 Create sets for each subsystem

In the activity 3.2 “Create sets for each subsystem”, the alternative design solutions were generated. The following paragraph clarifies how the nozzle is designed and suggests possible conceptual design solutions as illustrated in Fig. 7.

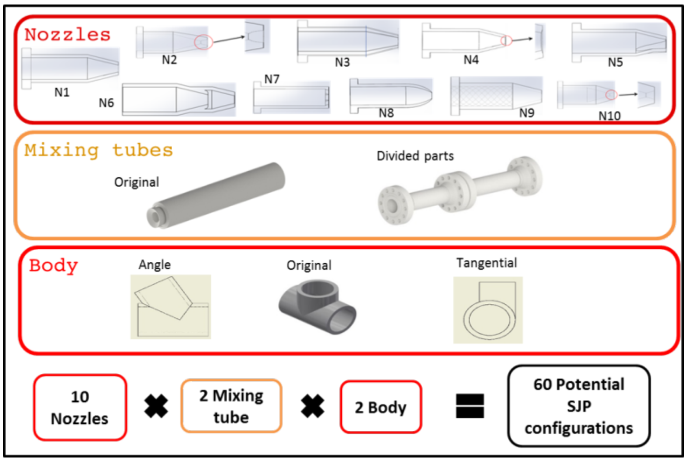

Fig. 6: Possible conceptual design solutions for each subsystem

The subsystem targets are taken into account during generation of the alternative designs as illustrated Fig. 6-B. In the next step, the defined boundaries have been considered in the SJP design process as depicted in Fig. 6-C. As a result, set of 10 nozzle, 2 mixing tube, 3 body design concepts have been generated based on the creativity which corresponds to the key value attributes. For the body, 2 different concepts were created together with the one from the original design using the same approach as for the nozzle in Fig. 7. In addition, mounts and flanges keep the same original design without any changes. The design space of the SJP could generate 60 potential systems as illustrated in Fig. 7 and it is calculated as follows:

(5) 10 (nozzle) x 2 (mixing tube) x 1 (mount) x 1 (flange) x 3 (body) = 60.

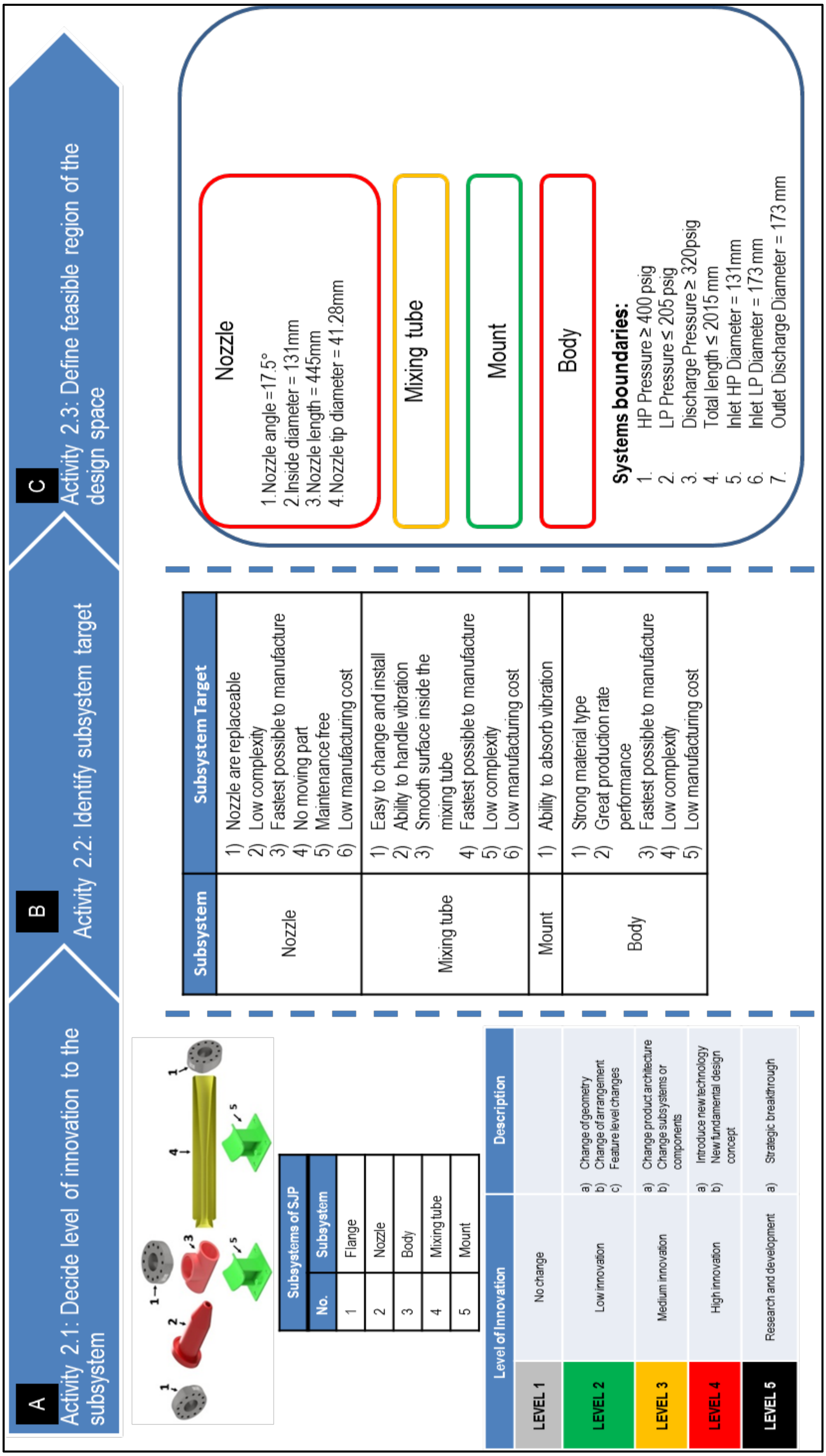

Fig. 7: The different sub-activities and their results of the SBCE activity 2 "Map the design space"

3.3 Explore subsystem sets: prototype & test

In activity 3.3 "Explore subsystem sets: prototype & test" , the conceptual solutions were evaluated. The analysis has been focused on the flow motion to determine the HP and LP values which give an impact to the performance of the SJP. The analyses were carried out for the nozzles by using the ANSYS CFX software as shows in Fig. 8. However, the analysis at this stage is done only for the nozzles as it is the only subsystem that could be analysed separately. Design variations are needed in order to obtain the highest velocity in the nozzle. This could produce a vacuum pressure, which helps to boost the pressure of LP fluid or gas to an intermediate pressure level.

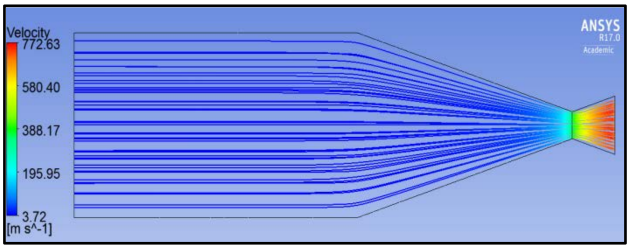

Fig. 8: Example of CFD result for nozzle N10

From the 60 potential SJP configurations, not all are suitable to become the final solution of the SJP. Therefore, trade-off curves were used to narrow down the subsystem solutions based on the CFD simulation results, manufacturing complexity and manufacturing cost of the solutions. The Trade-off Curves (ToCs) illustrated in Fig. 9 show the reduction of solutions from 10 to 3 following designs which is the N2, N4, and N10. These ToCs were generated based on simulation result and consultancies from Caltec.

In order to narrow down the 60 system configurations, ToCs were generated for the nozzle designs considering the KVA mentioned above. As it could be seen in Fig. 9, there are four design solutions of the nozzle in the feasible area. These are N1, N2, N4, and N10 which are illustrated in Fig. 7. As result of the analysis of the generated ToC in Fig. 9, the number of the nozzle designs were reduced from 10 to 4. Since the nozzle design, N1 is the original design, it is excluded from the design set. As a result from the nozzle ToCs analysis the configuration has been reduced from 60 to 18, the calculation are as follows:

(6) 3 (nozzle) x 2 (mixing tube) x 1 (flange) x 3 (body) = 18.

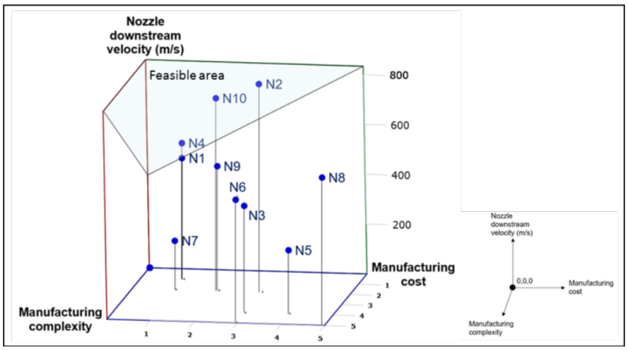

Fig. 9: 3D ToC comparing manufacturing complexity and manufacturing cost to nozzle downstream velocity

Phase 4: Converge on Systems

To obtain the final optimum SJP design, alternatives which are not increase the design performance were discarded and the rest of the possibilities have been developed until the optimum design solution was achieved.

4.1 Determine intersection of sets

In activity 4.1 "Determine intersections of set" , the final designs of SJP systems were generated using feasible subsystem set of solutions. From 18 possible solutions, not all of them should be considered in the final analysis. Two techniques were used in activity 4.1 "Determine intersections of set" in order to narrow down the set of solutions which is the CFD simulation of the SJP system as illustrated in Fig. 10 and the ToCs as shows in Fig. 11 . From both analyses, it gives two conclusions which are listed as follows;

- There is not necessary to divide the mixing tube (4) in Fig. 5 into parts as the length of mixing tube is only 1.3 m in the case study. However, if the length of mixing tube (4) is more than 5 m, the divided mixing tube is more economical to use as shows in Fig. 11 .
- The Body (3) designs with tangential and angle low pressure (LP) inlet were discarded due to their complexity and higher cost as well as it does not give a huge impact on the performance. Fig. 10 shows an example of the result of the SJP system using the CFD simulation.

As a result of the activity possible solutions were narrowed down from 18 to 3 which calculated as follows:

(7) 3 (nozzle) x 1 (mixing tube) x 1 (mount) x 1 (flange) x 1 (body) = 3

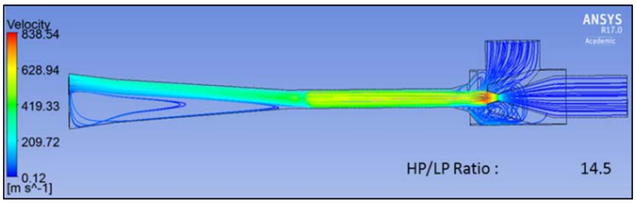

Fig. 10: Example of system analysis using CFD for nozzle N10

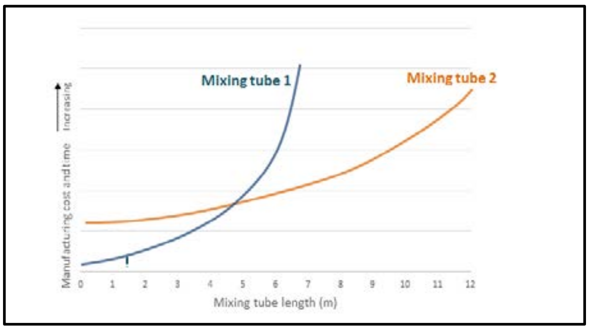

Fig. 11: ToC for Mixing tube; Manufacturing cost and time vs. Length of mixing tube

4.6 Converge on final set of system

In activity 4 "Converge on final set of system", an aggressive narrowing process has been implemented based on the loads of importance from the KVA and 3 ToCs which is design performance, manufacturability, and cost. Fig. 12 shows the ToC for the system design performance where systems are compared using HP pressure, LP pressure and HP/LP pressure ratio which obtained from the CFD simulation. The higher HP/LP pressure ratio results a better performance of the SJP hence improve the productivity of the SJP. Fig. 13-A and Fig. 13-B show the relation between manufacturing complexity, manufacturing cost and nozzle velocity. From the figures, the N10 system looks to be the optimum result in term of the manufacturability and cost. Even though N4 system gives the best result in manufacturability and cost, the velocity does not give a good impact to the performance of the SJP. Likewise, the N2 system give the best result in term of the performance (velocity) compared to others, however, it is not easy to manufacture due to its complexity. Nevertheless, the cost is the same between N2 system and N10 system.

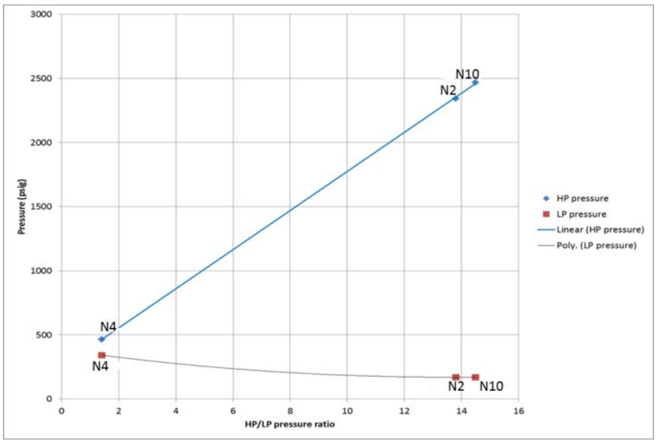

Fig. 12: ToC for HP/LP pressure ratio to HP and LP inlet pressure

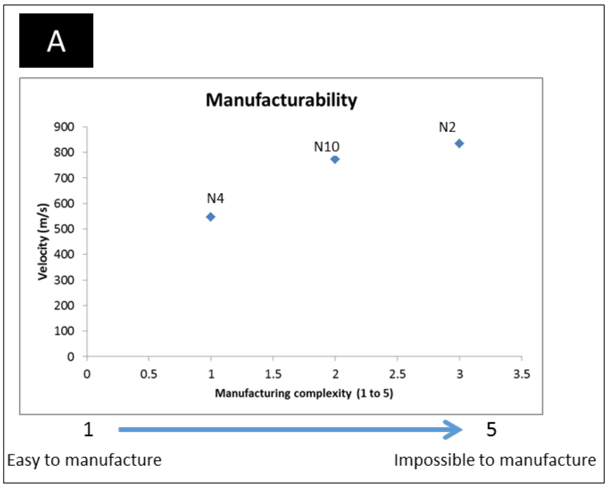

Fig. 13-A: ToC for Manufacturability

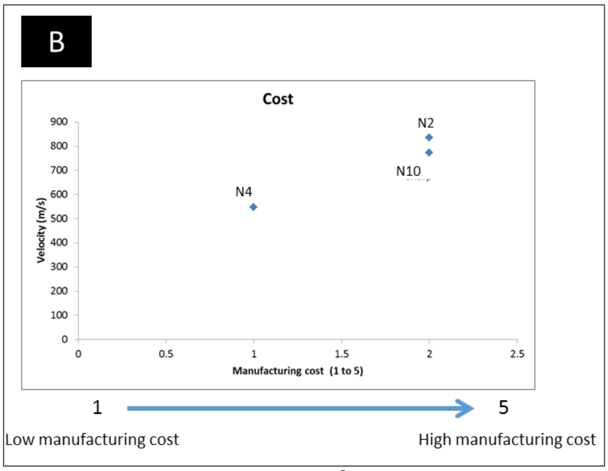

Fig. 14-A: ToC for Cost

To conclude the argument, the loads of importance weightage technique were used to evaluate the final optimum solution. At first, scale from 1 to 4 were used to identify the score of the systems as depicted in Fig. 14-A. The scale later on will be multiplied with the loads of importance from Fig. 4-E where the highest total weightage will be selected as the optimal solution. These were made through a several brainstorming sessions within research team based on the input from manufacturer, CFD simulation and ToCs. As a result, the optimal solution of the SJP is N10 system which gives the highest score of 2.53 as depicted in Fig. 14-B. Thus, the solution will be released to the final specification in the detailed design on Phase 5 "Detailed design".

A

Scale	
4	The Best
3	Good
2	Moderate
1	The Worst

B

KVA	Loads of importance	N4	N10	N2
Design performance	38.5%	1	4	3
Manufacturability	37.5%	3	2	1
Cost	24.0%	3	1	1
Total Weightage		2.23	2.53	1.77

Fig. 15: The loads of importance weightage based on the key value attributes (KVA)

Phase 5: Detailed Design

In this phase the final optimum solution of SJP system is presented. In this case study, only activity 5.1 "Release final specification" will be used.

5.1 Release final specification

In activity 5.1 "Release final specification", the final specification of SJP system design will be released. The final optimum solution N10 nozzle, original body and original mixing tube) is presented in technical drawing as shown in Fig. 18 where all the components are integrated as a system. Due to confidentiality of data, the engineering drawing for the final optimum solution are given without the dimensions as illustrated in Fig. 15.

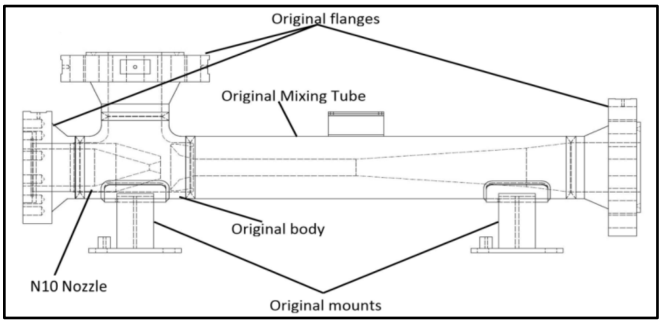

Fig. 16: Engineering drawing of the final optimum solution for system (N10)

4 Conclusion

This paper shows the detailed application of the Set-based Concurrent Engineering (SBCE) process model in the real industrial case study. This is achieved by considering an alternative set of solutions after gaining the right knowledge to support decision to narrow down the set of solutions until the single optimal design solution is reached. The SJP case study demonstrated the application of the SBCE process model in a systematic approach. This case study has benefited the company, by enhancing its current product development process by providing a space to explore alternative designs from different angles i.e. product performance, manufacturability, and cost. The SBCE approach guided the development of a SJP with the right design and engineering activities as well as the associated tools and method to enable the application of the different activities. In addition, the SBCE approach provided a suitable knowledge environment to support decision making throughout the development process. The innovation and knowledge creation level has increased where 60 system design configurations were identified through the application of the SBCE process model in the case study. The research proves that the SBCE has got the potential in producing high quality products in a short time and in a cost effective manner. Future work may consider a development of the business case for the SBCE applications as it could facilitates a valid justification in the expected benefits.

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